

A COMPARISON OF
Rowland's Thermometers with the Paris Standard,
AND A
REDUCTION OF HIS VALUE OF THE MECHANICAL EQUIVALENT
OF HEAT TO THE HYDROGEN SCALE.

A DISSERTATION
SUBMITTED TO THE BOARD OF UNIVERSITY STUDIES OF THE
JOHNS HOPKINS UNIVERSITY FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY.

BY
WILLIAM SCOFIELD DAY.

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A COMPARISON OF ROWLAND'S THERMOMETERS WITH THE PARIS STANDARD, AND A REDUCTION OF HIS VALUE OF THE MECHANICAL EQUIVALENT OF HEAT TO THE HYDROGEN SCALE.

BY WILLIAM S. DAY.

I. INTRODUCTION.

THE object of the investigation described here was to compare Professor Rowland's thermometers with the hydrogen scale of the International Bureau and to reduce his value of the mechanical equivalent accordingly.

The mechanical equivalent of heat, as it has been defined until recently, is, in the C. G. S. system, the value of J in the equation

$$J = \frac{dW}{dt}$$

where dW is the number of ergs required, when expended in heat, to raise the temperature of one gram of water dt° C. on the absolute scale. The use of the expression "mechanical equivalent" in its old sense will be adhered to in this paper for the sake of uniformity with Rowland's paper. This quantity, $\frac{dW}{dt}$, differs at different temperatures on account of the variation of the specific heat of water.

Rowland's measurement of the mechanical equivalent, in 1877-78¹ still remains as probably the best one in which the heat was

¹ Proc. Am. Acad., 15, p. 75, 1879.

produced by the expenditure of mechanical energy. Within the last few years, however, a number of other determinations have been made by electrical methods, and these have given values differing somewhat from Rowland's. The chief of these electrical determinations are those of E. H. Griffiths¹ and of Schuster and Gannon.² The following table, taken from Schuster and Gannon's paper, give some comparative values. The unit is the foot-pound at Greenwich ($g = 981.17$ cm. / sec.²) and the temperature scale is that of the Paris nitrogen thermometer.

	Joule.	Rowland.	Griffiths.	Schuster & Gannon.
At 19°.1 C	774	776.1	779.1	778.5
At 15°. C	775	778.3	780.2	779.7

The measurement of the quantity $\frac{dW}{dt}$ depends not only on the measurement of dW , but also on the scale of temperature used in measuring dt° . In Rowland's experiments this quantity was measured on the absolute scale, as determined by means of the air-thermometer. It was the object of the comparisons described here, to compare this absolute scale, as represented by Rowland's thermometers, with the hydrogen scale of the International Bureau of Weights and Measures, at Sèvres, near Paris. For this purpose there were secured three Tonnelot thermometers that had been studied at the International Bureau and compared with the standards of the Bureau at several points of the scale. These three thermometers were compared with three of Rowland's thermometers used in his mechanical equivalent experiment. The difference between Rowland's absolute scale and the Paris hydrogen scale was thus determined, and the corresponding corrections to the value of the mechanical equivalent were calculated. The general result is contained in Table IX. on page 218.

2. THERMOMETERS USED.

Rowland's value of the mechanical equivalent is the result of fourteen experiments, each of which was made with some one of four different thermometers in the calorimeter. In thirteen of these he used three thermometers made by Baudin in 1876-77, and in

¹ Phil. Trans., 184 A, p. 361, 1893.

² Phil. Trans., 186 A, p. 415, 1895.

one he used a thermometer made by Welsh in 1853, and called, in Rowland's paper, the Kew standard. This thermometer belongs to the University of Pennsylvania, and was not available for this comparison. The three Baudin thermometers were numbered 6163, 6165, and 6166. Of these, 6163 was used in eight experiments, 6165 in one experiment, and 6166 in four experiments. 6166 was also compared by Joule with one of his own thermometers.¹ The three Tonnelot thermometers were numbered 11,800, 11,801 and 11,811, and were made between November, 1895, and January, 1896. A complete study of these was made by the International Bureau, including a comparison at several points with the standards of the Bureau which had previously been compared with the hydrogen thermometer. Two of the thermometers, 11,800 and 11,811, were broken during their first transportation to America, but through the liberality and kindness of the International Bureau and of M. Guillaume, they were repaired by the maker, and a completely new study of them was made. These Tonnelot thermometers were made of French "verre dur," with transparent stems, and were divided into tenths of a degree. The Baudin thermometers were divided into millimeters. The centimeter marks were numbered, and corresponded in a rough way to degrees. The following table gives the dimensions and other data concerning these six thermometers.

TABLE I.
CONSTANTS OF THERMOMETERS.

Tonnelot Thermometers.			
Numbers.	11800	11801	11811
Division.	.1°	.1°	.1°
Total length.	701 mm.	704 mm.	679 mm.
Middle of bulb to zero of scale.	55.8 mm.	59.0 mm.	74.3 mm.
Length of a "degree" of the scale.	5.86 mm.	5.858 mm.	8.91 mm.
Value, in degrees centigrade, of one "degree" of the scale.	0.870604°	1.000014°	0.977160°
Baudin Thermometers.			
Numbers.	6163	6165	6166
Division.	Millimeters.	Millimeters.	Millimeters.
Total length.	501 mm.	500 mm.	497 mm.
Middle of bulb to zero of scale.	34 mm.	37 mm.	34 mm.
Value, in degrees centigrade, of one centimeter on stem.	1.114°	0.8470°	0.779°

¹ Rowland, Proc. Am. Acad., 16, p. 38, 1880.

3. MANNER OF USING THE THERMOMETERS.

In comparing these various thermometers, it was necessary to use them in the way in which they were originally used when they were standardized. The Tonnelot thermometers had to be used in the manner described by Guillaume in his "*Thermométrie de Précision*," and in the printed notice that came with the thermometers from the International Bureau. Rowland's thermometers were used in a different way when they were originally compared with the air-thermometer. The chief points of difference are in the corrections for internal and external pressure, and in the manner of taking and using the zero point. The present method, as used at the International Bureau, is to determine the pressure coefficients, as they are called, by means of which any variation in the external pressure from the standard 760 mm., due to a change in barometric pressure, or to immersing the thermometer in a liquid, and any internal hydrostatic pressure of the mercury on the bulb, due to the thermometer not being horizontal, can be taken account of and the proper corrections applied. There are two pressure coefficients, the external and the internal. The external pressure coefficient is generally denoted by the letter β_e , and gives the fraction of a degree the reading of the thermometer is changed by a change in the external pressure of 1 mm. of mercury. The internal pressure coefficient, β_i , can be calculated for French hard glass by adding the quantity 0.0000154 to the external coefficient. This quantity depends on the elastic constants of mercury and of glass. It is generally a small fraction, 10 per cent. or less, of the whole pressure coefficient. It differs, of course, for different kinds of glass, but this difference is a still smaller fraction of the whole pressure coefficient.

The zero point is always calculated from the zero taken immediately after each reading of temperature, before the zero has had time to change.

Rowland's thermometers were originally used in quite a different way. In his comparisons, the vertical position was considered as the normal one, and the thermometers were always used in that position. Changes in external pressure were not taken account of, except when they were caused by the pressure of water in the comparison tank. The thermometers, when not in use, remained at a

temperature of 18° to 20° C., the temperature of the room. The zero points were taken at the beginning of a series of comparisons. In taking the zeros the thermometers were immersed in ice for an hour or two before the reading was taken, and then the comparisons were made at successively higher temperatures. In order to reduce the readings of his thermometers to the air thermometer, Rowland found by calibration the apparent volume occupied by the mercury corresponding to each division line on the stem. He assumed that the temperature on the air thermometer was a function of the second degree of this volume. He made a number of comparisons between his thermometers and the air thermometer, and,

TABLE II.

Reduction of Rowland's Baudin thermometers to the air thermometer, and to the absolute scale. From p. 115 of Rowland's paper on the mechanical equivalent of heat,
 Column *A*. Reading in centimeters on the stem.
 Column *B*. Temperature on the air thermometer.
 Column *C*. Temperature on the absolute scale.

BAUDIN 6163.

<i>A</i>	<i>B</i>	<i>C</i>	<i>A</i>	<i>B</i>	<i>C</i>
5	$-0^{\circ}.911$	$-0^{\circ}.911$	24	20.350	20.345
5.81	0°	0°	25	21.457	21.452
6	$+0^{\circ}.214$	$+0^{\circ}.214$	26	22.559	22.55 ⁴
7	1 .328	1 .328	27	23.657	23.652
8	2 .461	2 .460	28	24.755	24.750
9	3 .584	3 .583	29	25.854	25.848
10	4 .707	4 .706	30	26.956	26.950
11	5 .829	5 .827	31	28.060	28.056
12	6 .950	6 .948	32	29.169	29.163
13	8 .071	8 .069	33	30.282	30.276
14	9 .193	9 .190	34	31.398	31.392
15	10 .314	10 .311	35	32.514	32.508
16	11 .435	11 .432	36	33.630	33.624
17	12 .556	12 .553	37	34.748	34.742
18	13 .676	13 .672	38	35.864	35.85 ⁷
19	14 .794	14 .790	39	36.979	36.972
20	15 .909	15 .905	40	38.094	38.087
21	17 .022	17 .018	41	39.206	39.199
22	18 .132	18 .127	42	40.316	40.309
23	19 .242	19 .237			

TABLE II.—*Continued.*

BAUDIN 6165.

<i>A</i>	<i>B</i>	<i>C</i>	<i>A</i>	<i>B</i>	<i>C</i>
3 cm.	−0°.457	−0°.457	23 cm.	17.009	17.005
3.5	0°	0°	24	17.861	17.857
4	+0°.457	+0°.457	25	18.714	18.709
5	1 .368	1 .368	26	19.562	19.557
6	2 .276	2 .275	27	20.406	20.401
7	3 .174	3 .173	28	21.247	21.242
8	4 .069	4 .068	29	22.081	22.076
9	4 .957	4 .955	30	22.912	22.907
10	5 .841	5 .839	31	23.736	23.731
11	6 .714	6 .712	32	24.552	24.547
12	7 .590	7 .588	33	25.370	25.365
13	8 .459	8 .456	34	26.180	26.174
14	9 .324	9 .321	35	26.987	26.981
15	10 .186	10 .183	36	27.788	27.782
16	11 .042	11 .039	37	28.590	28.584
17	11 .896	11 .893	38	29.382	29.376
18	12 .749	12 .746	39	30.176	30.170
19	13 .601	13 .598	40	30.971	30.965
20	14 .453	14 .450	41	31.782	31.786
21	15 .305	15 .302	42	32.577	32.581
22	16 .157	16 .153			

by the method of least squares, found the equation connecting the temperature and volume. From this he constructed a table for each thermometer giving the air thermometer temperature corresponding to each centimeter on the stem. These tables are given on pp. 115 and 116 of his paper on the mechanical equivalent, and are reproduced here in Table II. The corrections to reduce the air thermometer temperature to the absolute scale are deduced from the experiments of Thomson and Joule, and are given here as Rowland gives them on p. 114 of his paper. (Table III.)

4. INSTRUMENTS EMPLOYED.

In making these comparisons, it would have been theoretically better to have used the Baudin thermometers vertically and the Tonnelot thermometers horizontally, or at least both thermometers

TABLE II.—*Concluded.*

BAUDIN 6166.

<i>A</i>	<i>B</i>	<i>C</i>	<i>A</i>	<i>B</i>	<i>C</i>
2 cm.	−0°.034	−0°.034	23 cm.	16.298	16.294
3	+0°.759	+0°.759	24	17.074	17.070
4	1 .553	1 .553	25	17.849	17.845
5	2 .336	2 .335	26	18.627	18.622
6	3 .115	3 .114	27	19.405	19.400
7	3 .889	3 .888	28	20.182	20.177
8	4 .665	4 .664	29	20.960	20.955
9	5 .438	5 .436	30	21.735	21.730
10	6 .212	6 .210	31	22.511	22.506
11	6 .988	6 .986	32	23.292	23.287
12	7 .765	7 .763	33	24.075	24.070
13	8 .544	8 .542	34	24.855	24.850
14	9 .323	9 .321	35	25.634	25.628
15	10 .105	10 .102	36	26.412	26.406
16	10 .887	10 .884	37	27.195	27.189
17	11 .667	11 .664	38	27.982	27.976
18	12 .444	12 .441	39	28.768	28.762
19	13 .217	13 .214	40	29.550	29.544
20	13 .988	13 .984	41	30.339	30.333
21	14 .756	14 .752	42	31.123	31.117
22	15 .526	15 .522	43	31.914	31.908

TABLE III.

REDUCTION OF AIR THERMOMETER TO ABSOLUTE SCALE.

Air thermometer.	Correction to Air thermometer.
0°	0°
10°	−0°.0028
20°	−0°.0048
30°	−0°.0061
40°	−0°.0067
50°	−0°.0068

vertically. But in order to make it possible to remove the Tonnelot thermometers easily and quickly from the comparison tank in order to take the zeros, and also in order that the readings of the thermometers might be made with the micrometer telescope, it was decided to make the comparisons with the thermometers in a horizon-

tal position, as otherwise there would have been serious mechanical difficulties in the construction of the tank. This made it necessary to apply a pressure correction to the Baudin thermometers to make the readings what they would have been if the thermometers had been vertical, but this correction could be applied with considerable accuracy by measuring the pressure coefficients.

In carrying out these comparisons, it was found necessary to construct several pieces of apparatus. As some of these differed a little from any that had been used before, it will be necessary to give a short description of them.

a. *Pressure Apparatus.*

The pressure coefficients were determined in a manner practically identical with that described by Guillaume in his "Thermométrie de Précision," p. 104. Matters were so arranged that the thermometer could be subjected alternately to a pressure of 5 or 6 cm. of mercury, and then to the atmospheric pressure of 76 cm. The change in pressure was read by means of a mercury manometer, and the change in the reading of the thermometer was also noted. The method of taking the readings will be described later.

b. *Micrometer Telescope.*

The thermometers, in the comparison tank and in the zero tank, were always read by means of a micrometer telescope. The micrometer was not an eye-piece micrometer, but there were cross-hairs in the field of view, and the whole telescope was moved parallel to itself by the micrometer motion. The telescope was so constructed that it could be used to read the horizontal thermometers in the comparison tank, or the vertical thermometers in the zero tank. In reading vertical thermometers, the telescope was fastened to an upright frame, consisting of two vertical steel bars. It then became in effect a cathetometer. In all cases care was taken by means of levels and plumb-lines to have the axis of the telescope perpendicular to the thermometers. The telescope magnified about ten or eleven times.

c. *Comparison Tank.*

The comparison tank was devised to fulfill the following requirements :

1. The thermometers must be easily removed for the purpose of taking zeros.
2. They must remain at a practically constant temperature for four or five minutes.
3. They must be easily and quickly read by means of a micrometer telescope sliding on ways above the tank.
4. The supports on which the thermometers rest must be so solid and firmly fastened to the ways on which the telescope slides that there will be no possibility of any accidental relative motion of the telescope and the thermometer.

To fulfill the first requirement, it was decided to have a horizontal tank, as explained farther back. The tank was made of sheet copper in the form of a rectangular box 92 cm. long, 21 cm. wide and 23 cm. deep. A section of it is represented in Fig. 1, and a cross-section in Fig. 2. The top consisted of a movable lid made of a brass casting. This lid had a flange that was planed on the under side so as to fit a planed brass rim forming the top of the sides of the tank. A piece of sheet India rubber formed a packing between the two parts, to prevent the escape of water. After the lid had been placed in position, it could be screwed down tightly by means of a number of C-clamps placed around the sides. The lid was made in the form of a frame holding a piece of plate glass, which was a window through which the thermometers could be read. This window was about 1.5 cm. from the stems of the thermometers.

In order to fulfill the second requirement, the tank was placed inside a larger wooden box whose walls were everywhere about 5 cm. from the sides of the tank, and the intervening space was filled with cotton wool. This protected the tank very well except at the top, from too rapid a gain or loss of heat from the air when this was at a different temperature from that of the tank. The layer of cotton did not extend quite up to the top of the tank. The non-conducting layer above this point had to be easily removed, to allow the removal of the lid. A covering of felt was therefore constructed, about 2 cm. thick, which extended over all the parts of the tank not protected by the cotton, except the glass window. This had to be exposed, at least in part, to allow of reading the ther-

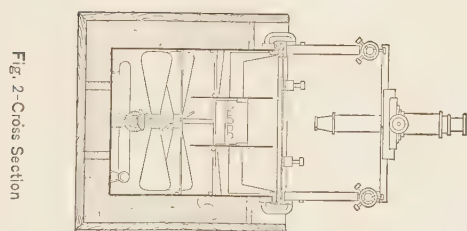
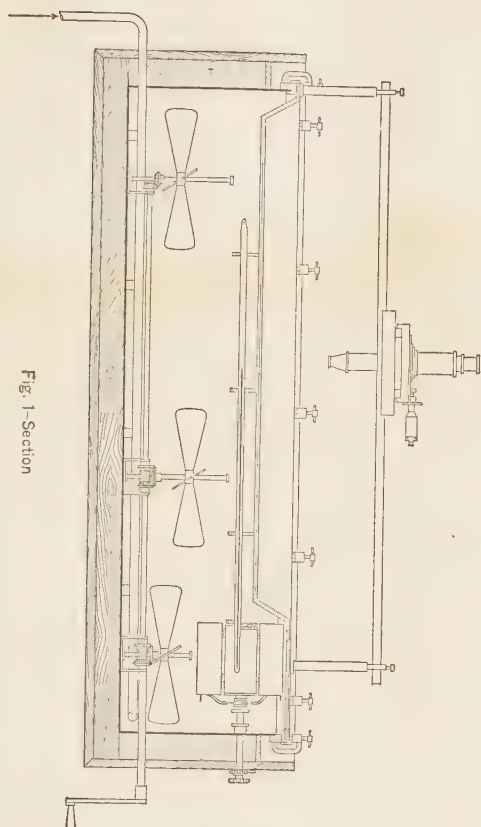
mometers. In order still further to protect the thermometers from any change of temperature, the bulbs were placed inside a brass box, as shown in the sections. This box was 10.5 cm. long, 8 cm. wide and 5 cm. deep. It was so constructed that two lids on the top, and two on the bottom, could be opened or closed from the outside of the tank. While the water was being stirred, in the manner to be described presently, this box was kept open. As soon as the water had attained a uniform temperature, and everything was ready to make a comparison, the stirring was stopped, and the lids of the box were closed. The bulbs were thus shut off completely from any convection currents, and in this manner the thermometers could be kept at a constant temperature for a considerable time. The water was stirred by three paddle wheels operated by means of a crank on the outside of the box.

In order to heat the water in the tank to bring it to any desired temperature, a brass tube ran along it from end to end, near the bottom. This did not communicate with the water of the tank, but opened into the air at each end. Steam was passed into it until the water reached the temperature desired.

Fastened to the lid of the tank were upright brass posts which held the ways on which the micrometer telescope slid. The telescope had freedom to move in two horizontal directions at right angles to each other, so that it could be placed quickly over any part of the tank, and used to read any thermometer at any part of its scale. The thermometers rested on little brass beams which were fastened to the brass rim of the tank. As this rim was clamped securely to the brass lid which carried the ways, the fourth requirement was secured. When the tank was full of water and the lid on, the thermometer bulbs were about 5.7 cm. below the surface of the water.

d. *Zero Tank.*

In taking the zero points of thermometers in the ordinary tank, it is necessary to plunge the thermometer down into the ice until the zero division is a good deal below the surface, so as to make sure that the stem is all at the temperature of 0° C. When a reading is made, the thermometer is raised until the zero point is just visible.



When this is done, not only is the stem apt to become covered with water in films and drops, which make it difficult to read the position of the mercury thread, but it is also apt to become covered with dew when the laboratory room, as is usual in this country, is at a temperature of from 16° to 20° C. When the zero point is near the bulb, there is also, it seems probable, some danger that a little warm water may trickle down the stem of the thermometer and find its way to the bulb in sufficient quantity to make a difference of several thousandths of a degree. In order to do away with these difficulties, it was decided to have the stem immersed in the ice for some distance above the zero-point, and to read the thermometer through a tube which should reach from the side of the tank to the part of the stem where the zero-point actually was. A device was therefore employed which is represented in Fig. 3. The ice was

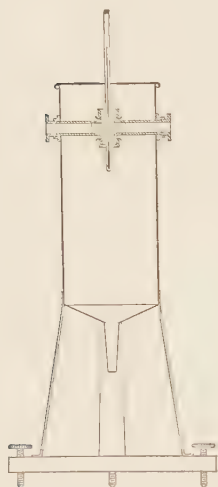


Fig. 3.—Zero Tank.

contained in a cylindrical tin-lined copper tank, 33.5 cm. high, and 15.2 cm. in diameter. At the bottom there was an opening through which the excess of water could be drawn off. At a distance of 7 cm. from the top of the tank, two openings 2 cm. in diameter were made, one on each side of the tank. To these there was fitted, in a manner that it is not necessary to describe, but so that it could be readily detached, a tube of hard rubber, or ebonite, 2 cm. in diameter. This ebonite tube extended horizontally across the tank from one side to the other, except that at the center of it there was a little brass piece that held a sort of drum with drum-heads of pure sheet rubber. These were perforated with small circular holes in the center, and a thermometer could be inserted perpendicularly through them both. When in position the whole tank could be filled with ice and water, and very little if any water escaped through the joints. As represented in the drawing, the two rubber diaphragms, or drum-heads, were 3.7 cm. apart, and a portion of the thermometer stem of that length was, therefore, not exposed to the ice. This portion of the stem, however, must have been within $0^{\circ}.1$

of 0° C., because when the bulb of a small thermometer which could detect a difference of $0^{\circ}.1$, was placed in the air in the center of this ebonite tube, and left there a short time, it indicated a temperature of 0° C. There was also no dew deposited on the stem unless there happened to be a draught of air blowing through the room, as happened in one or two cases.

In using the tank, the ice was broken up into very fine pieces by means of a wooden mallet in a zinc-lined wooden box, and transferred by a tin scoop to the zero tank. Ordinary distilled water was poured on it, and it was packed down closely. The thermometer was then placed in position, and the tank was filled to the brim with ice. The actual zero-point was generally observed in the middle of the tube. The water in the ice was also generally kept at about the same height. The actual height of the water was measured by means of a vertical glass tube placed alongside the tank, and communicating with the outlet tube at the bottom. A brass frame, not represented in the drawing, was fastened to the tank to support the thermometer.

The ice used was made artificially out of filtered Baltimore city water. Clear pieces were chosen, and it was found to be very pure by testing the water melted from it for ammonia, and for dissolved substances in general by measuring its electrical conductivity. The depression of the freezing point caused by impurities in the ice must have been less than $0^{\circ}.001$ C.

5. PRESSURE COEFFICIENTS.

a. *Exterior Pressure Coefficient.*

In measuring the exterior pressure coefficient, precautions were taken, following Guillaume, to have the thermometer bulb practically surrounded by a large mass of water which was at a temperature several degrees cooler than that of the room. The water in this grew warmer continuously and with great uniformity. This prevented errors due to a falling meniscus, as readings were not taken immediately after the pressure and the reading of the thermometer were reduced. Readings were taken alternately at atmospheric pressure, and at a pressure of 5–10 cm. of mercury. The average of the pair at the high pressure of one atmosphere was

compared with the intervening reading at a low pressure. Ten or twenty observations of this kind were made for each thermometer, and the results averaged. In this way the pressure coefficient in centimeters on the stem was found. As the bores of the thermometer tubes were not very uniform in diameter, this was reduced to degrees centigrade by means of Rowland's tables.

The observations are given in Table IV. The results are as follows :

For Baudin 6163, $\beta_e = 0^\circ.000274$.

For Baudin 6165, $\beta_e = 0^\circ.000296$.

For Baudin 6166, $\beta_e = 0^\circ.000318$.

b. *Interior Pressure Coefficient.*

In getting the interior pressure coefficient, the International Bureau, as mentioned before, calculates it from the external pressure coefficient. When the thermometer is made of French hard glass, the internal coefficient is connected with the external by the equation

$$\beta_i = \beta_e + 0.0000154$$

where the unit of measurement is degrees centigrade per millimeter of mercury pressure. Part of this difference depends on the cubical compression of mercury, and part on the elastic constants of the glass. The Baudin thermometers were not made of French hard glass, but it is probable that this difference would not be significantly changed by this fact. The same value has therefore been used. This gives for the three thermometers, the following values for the internal pressure coefficient.

For Baudin 6163, $\beta_i = 0^\circ.000290$.

For Baudin 6165, $\beta_i = 0^\circ.000311$.

For Baudin 6166, $\beta_i = 0^\circ.000334$.

TABLE IV.

Observations for Pressure Coefficient.

- Column *A*. Manometer reduced to 0° C. The pressure on the bulb of the thermometer = 1 atmosphere — the manometer reading.
 Column *B*. Thermometer reading, in centimeters on the stem.
 Column *C*. Means of pairs for manometer reading = 0 cm.
 Column *D*. Observed differences, due to the changes in pressure.

BAUDIN 6163.

<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>
0	21.296 cm.		
72.38 cm.	21.121	21.300 cm.	0.179 cm.
0	21.305		
69.71	21.137	21.310	.173
0	21.315		
67.10	21.153	21.318	.165
0	21.322		
64.54	21.168	21.326	.158
0	21.331		
62.25	21.183	21.335	.152
0	21.340		
59.77	21.194	21.345	.151
0	21.350		
57.59	21.208	21.353	.145
0	21.357		
57.72	21.217	21.360	.143
0	21.364		
57.33	21.224	21.369	.145
0	21.374		
58.02	21.231	21.376	.145
0	21.378		
57.95	21.239	21.381	.142
0	21.385		
59.08	21.242	21.390	.148
0	21.395		
59.87	21.251	21.397	.146
0	21.400		
59.83	21.256	21.403	.147
0	21.407		
59.64	21.266	21.412	.146
0	21.417		
59.58	21.272	21.419	.147
0	21.422		
58.13	21.280	21.425	.145
0	21.428		
58.98	21.286	21.432	.146
0	21.436		
58.98	21.293	21.438	.145
0	21.441		
58.88	21.300	21.444	.144
0	21.447		
1217.33			3.012

12173.3 $\beta_e = 3.012$ cm.

$\beta_e = .000247$ cm. per mm. mercury pressure.

$\beta_e = 0^\circ.000274$ per mm. mercury pressure.

TABLE IV.—*Continued.*

BAUDIN 6165.

<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>
0	23.088		
66.5	22.868	23.094	0.226
0	23.100		
64.3	22.885	23.109	.224
0	23.118		
62.2	22.909	23.127	.218
0	23.135		
61.3	22.928	23.142	.214
0	23.150		
60.4	22.948	23.157	.209
0	23.164		
59.8	22.965	23.171	.206
0	23.179		
59.4	22.982	23.187	.205
0	23.196		
59.2	23.000	23.202	.202
0	23.209		
58.5	23.015	23.218	.203
0	23.228		
58.6	23.033	23.235	.202
0	23.243		
58.4	23.049	23.251	.202
0	23.260		
58.0	23.065	23.268	.203
0	23.277		
58.9	23.079	23.285	.206
0	23.293		
59.4	23.093	23.302	.209
0	23.311		
59.3	23.114	28.320	.206
0	22.329		
59.1	23.131	23.338	.207
0	23.347		
58.9	23.150	23.357	.207
0	23.367		
59.8	23.166	23.375	.209
0	23.384		
59.3	23.186	23.393	.207
0	23.403		
1141.3			3.965

11413 $\beta_e = 3.965$ cm. $\beta_e = 0.000347$ cm. per mm. mercury pressure. $\beta_e = 0^{\circ}.000296$ per mm. " "

TABLE IV.—*Concluded.*

BAUDIN 6166.

<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>
0	24.147		
61.1	23.900	24.153	.253
0	24.160		
59.0	23.927	24.171	.244
0	24.183		
56.8	23.955	24.190	.235
0	24.198		
56.2	23.980	24.208	.228
0	24.218		
56.0	24.000	24.228	.228
0	24.238		
55.5	24.014	24.245	.231
0	24.253		
53.5	24.038	24.258	.220
0	24.263		
51.6	24.062	24.270	.208
0	24.278		
49.8	24.084	24.286	.202
0	24.294		
48.0	24.109	24.308	.199
0	24.322		
547.5			2.248

5475 $\beta_e = 2.248$ cm. $\beta_e = .000411$ cm. per mm. mercury pressure. $\beta_e = 0^{\circ}.000318$ per mm. " "

6. MANNER OF MAKING THE COMPARISONS.

In comparing a Tonnelot with one of the Baudin thermometers, the Baudin was placed first in ice for two or three hours. Its zero point was then read by means of the micrometer telescope three or four times in succession, and the average taken as the reading. In the meantime the water in the comparison tank having been cooled to about 10° or lower, the Baudin and one of the Tonnelot thermometers were placed in the tank. The top of the tank was put on, and while the box containing the bulbs re-

mained open, the water was thoroughly stirred. As long as the temperature of the water in the tank was lower than that of the room, it of course rose very slowly while the stirring went on. This sufficed to make the thermometers always reach any given temperature below that of the room with a rising meniscus. As soon as the water was thoroughly mixed, the stirring was stopped, and the inner box immediately closed. A micrometer reading of the mercury thread on one of the thermometers was then taken quickly, the telescope shifted quickly to the other thermometer, and a reading taken of it. A second reading of both thermometers was also taken. Of course, the first readings were the most reliable, but when there was no delay, there was hardly ever any appreciable change of temperature observed on reading the second time, except sometimes at the extreme temperature of 40° . The second reading was taken more as a check on the first, to make sure there was no error in reading. Having made this observation at a certain temperature, the inner box was opened, the water stirred up again, and another comparison made in the same way. This would be, of course, at a slightly higher temperature. These readings at two neighboring temperatures were averaged, and the average regarded as one reading. When the temperature was higher than that of the room, the only difference made was that steam was passed into the heating tube just before a reading was taken. The water was stirred, and the thermometers were brought to the position in which they were read with a rising meniscus, and not with a falling one. This was made very sure by observing one of the thermometers through the telescope while the heating and stirring was going on. Having made two observations at neighboring temperatures, the top of the tank was taken off, the Tonnelot thermometer removed, and its zero determined. The Tonnelot thermometer was then replaced, the top of the tank put on, the water heated, and a comparison made in the same way at the next temperature. It was not possible conveniently to make comparisons at many points in one day. The intention was, therefore, to take observations roughly at 10° , 20° , 30° and 40° . This was only approximately carried out, as it sometimes became convenient, for a good many reasons, to use temperatures intermediate to these.

7. COMPARISONS MADE.

A number of comparisons were made between the Tonnelot thermometers taken in pairs, between the Tonnelot and Baudin thermometers, and between the Baudin thermometers. The results of these comparisons are given in Tables V. and VII. The comparisons may seem to be rather few in number, but it was not thought worth while to make any more, considering all the circumstances. It must be remembered that the readings of the thermometers were made micrometrically, so that the errors in reading are exceedingly small. Such large experimental errors as there are, must be probably in connection with the position of the zero. Rowland always read his thermometers with the naked eye, and although this was the only practicable way of using them in his experiment, the fact must be considered in making any comparisons between his thermometers and any others.

Two comparisons were made between Tonnelot 11,801 and Tonnelot 11,811, and three between Tonnelot 11,800 and Tonnelot 11,811. In one of the latter comparisons, that of 21 April, the thermometer 11,811 became accidentally heated up to 30° before a reading at 20° was taken, and for this reason, on account of the recovery of the zero being in progress while the comparison was being made, it was thought probable that some irregularity would be shown. This proved to be the case, although it is not certain that the irregularity was due to the overheating. There were also other disturbing influences that made it seem probable at the time that the comparison would not be reliable. The comparison, however, was rejected. In comparing the Tonnelot thermometers, they were always placed in ice for some hours before a comparison was begun, in case the first temperatures used were lower than the temperature to which the thermometer had been exposed for some time previously, so that the recovery of the zero might have a chance to proceed as far as possible before the comparisons were begun. The results of the comparisons of the Tonnelot thermometers with each other are given in Table V. The two comparisons of each pair seemed to agree so well that, without taking any further time to make more comparisons, it was decided that they represented substantially the difference between the thermometers. From these

comparisons smooth correction curves were drawn, so that the readings of the thermometers 11,800 and 11,811 could be reduced to those of 11,801. These corrections, however, are small, amounting in most cases to only a few thousandths of a degree. A table of these corrections, deduced from the smooth curves, is given in Table VI.

TABLE V.

Comparisons of Tonnelot thermometers with each other.

11801 and 11811 compared.

Observed readings.		Readings reduced to the hydrogen scale.		
Tonnelot. 11801	Tonnelot. 11811	Tonnelot. 11801	Tonnelot. 11811	11801 -11811
12 April, 1897.				
10°.529	10°.615	10°.421	10°.423	-°.002
25 .470	25 .981	25 .338	25 .344	- .006
36 .643	37 .354	36 .478	36 .475	+ .003
14 April, 1897.				
7°.681	7°.682	7°.570	7°.570	°.000
24 .562	25 .051	24 .432	24 .436	- .004
36 .725	37 .438	36 .560	36 .559	+ .001

11800 and 11811 compared.

Tonnelot. 11800	Tonnelot. 11811	Tonnelot. 11800	Tonnelot. 11811	11800 -11811
21 April, 1897.				
7°.196	8°.019	7°.898	7°.899	-°.001
20 .180	19 .610	19 .143	19 .140	+ .003
29 .925	28 .324	27 .598	27 .607	- .009
38 .783	36 .165	35 .297	35 .308	- .011
23 April, 1897.				
9°.523	10°.079	9°.896	9°.896	°.000
21 .232	20 .554	20 .053	20 .059	- .006
30 .961	29 .246	28 .500	28 .504	- .004
40 .879	38 .022	37 .123	37 .132	- .009
27 April, 1897.				
7°.966	8°.702	8°.570	8°.568	+°.002
20 .299	19 .725	19 .252	19 .257	- .005
32 .595	30 .689	29 .927	29 .933	- .006
40 .773	37 .929	37 .035	37 .041	- .006

TABLE VI.

Corrections for reducing the readings of Tonnelot 11800 and 11811 after reduction to the hydrogen scale, to the hydrogen scale as represented by Tonnelot 11801. These corrections are the ordinates of the smooth curves which were deduced from the comparisons given in Table V.

Temperature.	$T_{01}-T_{00}$	$T_{01}-T_{11}$
2°	0	0
4	0	0
6	-0.001	-0.001
8	-0.001	-0.001
10	-0.001	-0.001
12	-0.001	-0.002
14	0	-0.002
16	0	-0.003
18	+0.002	-0.003
20	+0.001	-0.004
22	+0.001	-0.005
24	0	-0.005
26	+0.001	-0.004
28	+0.002	-0.003
30	+0.003	-0.002
32	+0.005	-0.001
34	+0.006	0
36	+0.008	+0.001

TABLE VII.

Comparisons between Tonnelot and Baudin thermometers.

Observed Readings.		Reduced Readings.		Differences. $T-B$
Tonnelot.	Baudin.	Tonnelot. <i>H</i> —scale.	Baudin. Abs. scale.	

23 March, 1897.

Tonnelot 11801 and Baudin 6163.

At beginning, observed zero of Baudin	6163	6.021 cm.		
" " reduced zero of Baudin	6163	+0°.238.		
7°.055	12.236 cm.	6°.941	6°.932	+0°.009
14 .161	18.598	14 .050	14 .041	+ .009
25 .335	28.708	25 .202	25 .198	+ .004
33 .044	35.678	32 .910	32 .916	- .006
40 .509	42.364	40 .328	40 .344	- .016

29 March, 1897.

Tonnelot 11811 and Baudin 6163.

At beginning, observed zero of Baudin,	6.029 cm.			
" " reduced zero of Baudin,	+0°.243.			
10°.329	15.106 cm.	10°.141	10°.131	+0°.010
18 .166	21.928	17 .743	17 .729	+ .014
29 .969	32.364	29 .226	29 .219	+ .007
37 .227	38.777	36 .357	36 .356	+ .001

TABLE VII.—*Continued.**Comparisons between Tonnelot and Baudin Thermometers.*

Observed readings.		Reduced readings.		Differences. <i>T—B</i>
Tonnelot.	Baudin.	Tonnelot. <i>H—scale.</i>	Baudin. <i>Abs. scale.</i>	
31 March, 1897.				
<i>Tonnelot 11800 and Baudin 6163.</i>				
At beginning,	observed zero of Baudin,	6.021 cm.		
“ “	reduced zero of Baudin,	+0°.234.		
9°.361	14.756 cm.	9°.755	9°.748	+0°.007
20 .231	23.228	19 .188	19 .176	+ .012
30 .385	31.255	28 .002	28 .001	+ .001
39 .410	38.320	35 .846	35 .857	— .011
24 March, 1897.				
<i>Tonnelot 11801 and Baudin 6165.</i>				
At beginning,	observed reading of Baudin,	3.823 cm.		
“ “	reduced zero of Baudin,	+0°.299.		
10°.442	15.586 cm.	10°.338	10°.331	+0°.007
19 .568	26.327	19 .454	19 .446	+ .008
28 .854	37.731	28 .737	28 .740	— .003
26 March, 1897.				
<i>Tonnelot 11811 and Baudin 6165.</i>				
At beginning,	observed zero of Baudin 6165,	3.818 cm.		
“ “	reduced zero of Baudin 6165,	+0°.290.		
9°.624	14.565 cm.	9°.467	9°.461	+ .006
22 .358	29.161	21 .817	21 .818	— .001
30 .301	38.756	29 .551	29 .554	— .003
1 April, 1897.				
<i>Tonnelot 11800 and Baudin 6165.</i>				
At beginning,	observed zero of Baudin 6165,	3.824 cm.		
“ “	reduced zero of Baudin 6165,	+0°.292.		
10°.971	16.530 cm.	11°.153	11°.133	+ .020
18 .209	23.930	17 .434	17 .415	+ .019
31 .533	38.062	29 .004	28 .999	+ .005
24 March, 1897.				
<i>Tonnelot 11801 and Baudin 6166.</i>				
At beginning,	observed zero of Baudin 6166	2.420 cm.		
“ “	reduced zero of Baudin 6166	+0°.305.		
10°.521	15.844 cm.	10°.417	10°.399	+0°.018
19 .573	27.544	19 .459	19 .420	+ .039
28 .645	39.242	28 .528	28 .509	+ .019
26 March, 1897.				
<i>Tonnelot 11811 and Baudin 6166.</i>				
At beginning,	observed zero of Baudin 6166	2.417 cm.		
“ “	reduced zero of Baudin 6166	+0°.297.		
9°.613	14.610 cm.	9°.456	9°.440	+ .016
21 .795	29.896	21 .270	21 .241	+ .029
30 .190	40.415	29 .442	29 .428	+ .014

TABLE VII.—*Concluded.**Comparisons between Tonnelot and Baudin thermometers.*

Observed Readings.		Reduced Readings.		Differences. <i>T-B</i>
Tonnelot.	Baudin.	Tonnelot.	Baudin.	
		<i>H</i> —scale.	Abs. scale.	
1 April, 1897.				
<i>Tonnelot 11800 and Baudin 6166.</i>				
At beginning,	observed zero of Baudin	6166	2.418 cm.	
“ “	reduced zero of Baudin	6166	+0°.293.	
10°.861	16.664 cm.	11°.057	11°.038	+ .019
18 .171	24.896	17 .402	17 .372	+ .030
31 .143	39.417	28 .664	28 .648	+ .016

26 April, 1897.

Tonnelot 11801 and Baudin 6163.

At beginning,	observed zero of Baudin	6163	6.006.	
" "	reduced zero of Baudin	6163	+0°.221.	
9°.539	14.454 cm.	9°.432	9°.427	+ .005
19 .674	23.550	19 .555	19 .548	+ .007
30 .825	33.691	30 .707	30 .721	— .014
39 .512	41.454	39 .331	39 .354	— .023

Next a series of comparisons was made between each Tonnelot thermometer and each Baudin. The results of these comparisons are given in Table VII., p. 213. The readings of the Tonnelot thermometers were reduced to the hydrogen scale, applying all the corrections supplied by the International Bureau, and the corrections mentioned in the last paragraph, required to reduce the readings to those of Tonnelot 11801. Tonnelot 11801 was chosen for this purpose because it was the one which had not been broken. Each of these comparisons gave a correction curve, the ordinates of which represented the corrections that must be applied to the readings of the Baudin thermometers, when reduced to the absolute scale, to reduce them to the hydrogen scale, as represented by the Tonnelot thermometers. From these three curves for each Baudin thermometer there was deduced an average correction curve for each. The ordinates of this final smooth curve for each Baudin thermometer are given in Table VIII., p. 216. As there were three thermometers of each kind, there were nine possible compari-

TABLE VIII.

Corrections to be added to the readings of the Baudin thermometers, when they have been reduced to the absolute scale, to reduce them to the Paris hydrogen scale, as represented by Tonnelot 11801. These corrections are the ordinates of the smooth curves which were deduced from the comparisons given in Table VII. The corrections are given in thousandths of a degree.

Temp.	6163	6165	6166	Temp.	6163	6165	6166
1°	+ 1	+ 1	+ 2	21°	+10	+ 8	+31
2	2	3	3	22	9	7	30
3	3	4	5	23	8	6	29
4	4	5	6	24	7	5	27
5	5	6	8	25	6	4	25
6	6	7	10	26	5	3	23
7	6	8	12	27	4	2	21
8	7	9	13	28	3	1	19
9	8	10	15	29	2	0	16
10	9	11	17	30	1	-1	13
11	9	11	19	31	- 1	-2	10
12	10	12	21	32	- 2	-3	7
13	10	11	23	33	- 3	-4	
14	11	11	25	34	- 5		
15	11	11	27	35	- 6		
16	11	10	29	36	- 7		
17	11	10	30	37	- 8		
18	11	9	31	38	- 9		
19	11	9	32	39	-10		
20	10	8	32	40	-11		

sons. These nine were all made, and finally an additional one on April 26, 1897, between Tonnelot 11801 and Baudin 6163. When this was made the Baudin thermometer had not yet recovered its zero from a depression caused by frequent use up to within six days of the time of the comparison. Its correction curve therefore differed from the others, but in the way one would expect on account of this depression. It was, however, rejected. The corrections given in Table VIII. were finally used to calculate the changes to be made in Rowland's value of the mechanical equivalent to reduce it to the Paris hydrogen scale.

In order to get a further check on the comparisons, the three Baudin thermometers were placed in the tank at the same time, and

compared together. Without going into the details here, it may be said that these comparisons verified the results, so far as it was possible, of the other comparisons.

8. CALCULATION OF THE EFFECT ON ROWLAND'S VALUE OF THE MECHANICAL EQUIVALENT OF HEAT.

In order to estimate the effect of these corrections to the Baudin thermometers on the value of the mechanical equivalent of heat, the experiments made by Rowland with each thermometer were considered separately. Rowland has a table on p. 192 of his paper giving the mechanical equivalent, in kilogram-meters at Baltimore, each value calculated from a rise of 10° in temperature, as deduced from each of his experiments. From this table the mean value of the mechanical equivalent at each temperature was calculated, as obtained by each thermometer separately. Rowland's value was deduced from an equation of the form

$$J = \frac{W}{10^\circ}$$

where W is a certain number of ergs, found by experiment, required to raise the temperature of 1 gram of water 10° C. J at 12° , for example, was calculated from the value of W in going from 7° to 17° C. That is

$$J_{12} = \frac{W}{17^\circ - 7^\circ}$$

If C_{17} and C_7 are the corrections found for the readings of the Baudin thermometer, to reduce them to the hydrogen scale, these corrections, applied to the value of J_{12} will give the corrected value of J_{12} , which shall be called J_{12}' . This gives

$$J_{12}' = \frac{W}{17^\circ + C_{17} - (7^\circ + C_7)} = \frac{W}{10^\circ + C_{17} - C_7}$$

$$\therefore J_{12}' = \frac{W}{10} \cdot \frac{10}{10 + C_{17} - C_7} = J_{12} \frac{10}{10 + C_{17} - C_7}$$

When $C_{17} - C_7$ is very small, as is always the case in these corrections, this may be written

$$J_{12}' = J_{12} \left(1 - \frac{C_{17} - C_7}{10} + \dots \right) = J_{12} + J_{12} P_{12}$$

where

$$P_{12} = \frac{C_7 - C_{17}}{10}$$

This conversion factor, P_{12} , was calculated similarly for each degree of the scale where it was necessary, and for each thermometer, and the corresponding value of J' calculated. Then taking account of the number of observations on each thermometer, used in getting the average value of J , these corrected values were averaged for each degree at which observations were made. The resulting values are given in Table IX. These values were plotted, and a smooth curve drawn in the neighborhood of the points. The ordinates deduced from this smooth curve give the corrected value of the me-

TABLE IX.

General result of comparisons.

Column *A*. Temperatures on absolute scale.

Column *B*. Corrected values of the mechanical equivalent of heat, hydrogen scale, kilogrammeters at Baltimore, from smooth curve.

Column *C*. Same, converted to the C. G. S. system.

Column *D*. Old values, from Rowland's paper, Table 54, p. 196.

<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>
5°			4212	21°	426.5	4180	4177
6	428.9	4203	4209	22	426.4	4179	4176
7	428.7	4201	4207	23	426.3	4178	4175
8	428.5	4199	4204	24	426.2	4177	4174
9	428.3	4198	4202	25	426.1	4176	4173
10	428.1	4196	4200	26	426.1	4176	4172
11	427.9	4194	4198	27	426.0	4175	4171
12	427.7	4192	4196	28	426.0	4175	4171
13	427.6	4191	4194	29	425.9	4174	4170
14	427.4	4189	4192	30	425.9	4174	4171
15	427.3	4188	4189	31	425.9	4174	4171
16	427.1	4186	4187	32	425.9	4174	4171
17	427.0	4185	4185	33	425.9	4174	4172
18	426.9	4184	4183	34	425.9	4174	4172
19	426.7	4182	4181	35	426.0	4175	4173
20	426.6	4181	4179	36	426.0	4175	4173
		×10 ⁴	×10 ⁴			×10 ⁴	×10 ⁴

chanical equivalent in kilogram-meters at Baltimore, as deduced from the comparisons described here. These values are given in Table IX. in kilogram-meters, and also in the C. G. S. system. They are also shown in the curves in Fig. 4. On this diagram

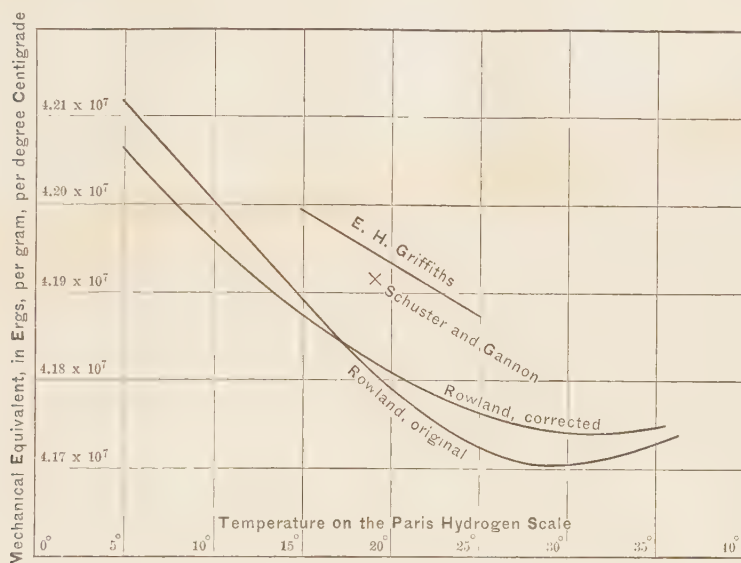


Fig. 4.

are drawn curves representing Rowland's uncorrected values, the corrected values, as given in Table IX., and the values obtained by E. H. Griffiths, after correcting them to the hydrogen scale.¹ Griffiths' values were corrected to the hydrogen scale from the nitrogen scale by means of the differences between the two scales, as given by the experiments of Chappuis.² Schuster and Gannon's value, 4.1917×10^7 at $19^\circ.1$, is also marked on the same diagram for comparison.³

9. SCHUSTER'S INDIRECT COMPARISON OF BAUDIN 6166 WITH THE PARIS NITROGEN THERMOMETER.

Before the comparisons described here were made, one of Rowland's thermometers had already been compared indirectly with

¹ Phil. Trans., 186 A, p. 361, 1893; Phil. Mag., 40, 447 and 437, 1895.

² Guillaume, Thermométrie de Précision, p. 258.

³ Phil. Trans., 186 A, p. 458, 1895.

the Paris nitrogen thermometer. In the summer of 1879, Joule himself made a comparison of Rowland's thermometer, Baudin 6166, with his own thermometer, and the results were published by Rowland.¹ In 1892-94, Schuster made a comparison of Joule's thermometer with a Tonnelot that had been standardized at the International Bureau, and he reduced the indications of the Joule thermometer to the Paris nitrogen scale.² These two comparisons should give a means of reducing the indications of Rowland's thermometer to the Paris nitrogen or hydrogen scale. The present writer has made an examination of the comparisons of Schuster and of Joule, and, by means of a graphic method, the results obtained by Schuster's indirect comparison were compared with those obtained from the present series. The curves drawn are shown in Fig. 5. The notation used is intended to be suggestive of the meaning of the curves. The ordinates of the

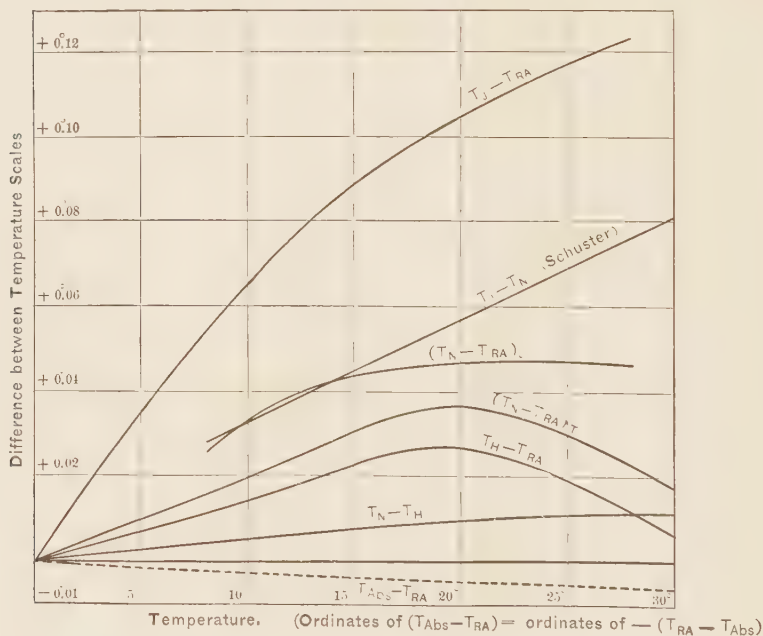


Fig. 5.

¹Proc. Am. Acad., Vol. 16, p. 38, 1880-81.

²Schuster, Phil. Mag., Vol. 39, p. 477, 1895.

curve marked $T_{RA} - T_{Abs}$ give the differences between the air thermometer and the absolute scale, as used by Rowland. The ordinates of the curve $T_N - T_H$ represent the differences between the nitrogen and the hydrogen scale, according to Chappuis. The ordinates of the curve $T_H - T_{Abs}$, which is not shown in Fig. 5, represent the differences between the hydrogen scale and Rowland's absolute scale according to Baudin 6166, as given by the present series of comparisons. (See Table VIII.) In order to get the ordinates of the curve $(T_N - T_{RA})_T$, which represents the differences between the Paris nitrogen scale and Rowland's air thermometer scale according to Baudin 6166 and the Tonnelot thermometers, the ordinates of the curves were added, as represented by the following equation :

$$(T_H - T_{Abs}) - (T_{RA} - T_{Abs}) + (T_N - T_H) = (T_N - T_{RA})_T.$$

In a similar manner the curve $T_J - T_{RA}$ is the smooth curve which represents approximately the differences found by Joule between his thermometer and Rowland's air thermometer, according to Baudin 6166. The curve $T_J - T_N$, which is a straight line, is taken to represent the differences between Joule's thermometer and the Paris nitrogen thermometer, according to the comparisons of Schuster. Schuster does not give this curve, but merely its slope. If the points found by his experiments are plotted on section paper, the straight line

$$(T_J - T_N) = 0^{\circ}.0024 T_N + 0^{\circ}.009$$

which has the slope he gives, seems most nearly to represent the average of the points. The final curve $(T_N - T_{RA})_J$ is found by subtracting ordinates as represented by the equation

$$(T_J - T_{RA}) - (T_J - T_N) = (T_N - T_{RA})_J$$

As shown in Fig. 5, this curve is not very unlike the curve $(T_N - T_{RA})_T$. The maxima are near 20° in both, and the difference between the two is about $0^{\circ}.01$, which is not very great in view of the ignorance as to how Joule made his comparisons, and the chances of a weak point in so long a chain.

10. CONCLUSION.

These comparisons do not explain the discrepancy between Rowland's value of the mechanical equivalent of heat, and the higher val-

ues found by recent experimenters using electrical methods. They seem to show, however, that the discrepancy is not one of thermometry. It is probable, therefore, that it is due to some error in the measurement of energy in Rowland's experiments, or to a similar error in the electrical experiments. In Griffiths' measurement of electrical energy expended in heat, the square of the electromotive force enters as a factor in the value of J . This makes any error in the measurement of this quantity have double the effect on the value obtained for J . An error in the standard of electromotive force of about one-tenth per cent. would, therefore, suffice to account for the entire difference between Rowland's results and Griffiths'.

The most interesting result of the present comparison is that Rowland's corrected curve shows the same rate of change in the specific heat of water with the temperature between 15° and 25° that Griffiths' does, as can be seen at a glance by an inspection of the curves as drawn in Fig. 4. This fact also suggests the possibility of the difference being due to an error in the standards used, rather than in the experiments themselves.

A short abstract of the results of these comparisons was published in the Johns Hopkins University Circular for June, 1897, giving the corrected values of the mechanical equivalent of heat. There was a slight error in the values as published, owing to the use of an incorrect method of reducing the readings of Rowland's Baudin thermometers. The error was not discovered until after the abstract had been published. This incorrect abstract was reproduced in the *Philosophical Magazine* for August, 1897.

The author wishes to express his appreciation of Professor Rowland's kindness in allowing the use of his thermometers for these comparisons, and his obligation to Professor Rowland and Professor Ames for their frequent aid and advice in the course of the work.

Although the general plan of the apparatus described here is the author's, he wishes to express his deep sense of obligation to Dr. W. T. Mather, at that time Fellow of Johns Hopkins University, for his aid at almost every step in the mechanical details of its design and construction.

COLUMBIA UNIVERSITY, NEW YORK.

The author was born in New York City on the 2d of January, 1864. He was educated in private schools in that city, and in October, 1880, he entered the academic department of Columbia College. He graduated in June, 1884, receiving the degree of A. B. He then entered business life, in which he remained until 1891. In October of that year he entered the Johns Hopkins University as a graduate student in Physics. In 1895-96 he was appointed a student-assistant in the Physical Laboratory of the Johns Hopkins University.

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